# Supergalactic winds driven by multiple superstar clusters.

Guillermo Tenorio-Tagle [1], Sergiy Silich [1] and Casiana Muñoz-Tuñón [2]


## ABSTRACT

Here we present two dimensional hydrodynamic calculations of free expanding supergalactic winds, taking into consideration strong radiative cooling. Our main premise is that supergalactic winds are powered by collections of superstar clusters, each of which is a source of a high metallicity supersonic diverging outflow. The interaction of winds from neighboring superstar clusters is here shown to lead to a collection of stationary oblique shocks and crossing shocks, able to structure the general outflow into a network of dense and cold, kpc long filaments that originate near the base of the outflow. The shocks also lead to extended regions of diffuse soft X-ray emission and furthermore, to channel the outflow with a high degree of collimation into the intergalactic medium.


*Subject headings:* Galaxies: superwinds, Starbursts: optical and X-ray emissions, general - starburst galaxies

## 1. Introduction

Supergalactic winds (SGWs; see Heckman 2001), as first envisaged by Chevalier and Clegg (1985; hereafter CC85), freely flow from the nuclear starburst region of a galaxy into the intergalactic space. The flow originally thought to behave in an adiabatic manner has recently been shown to be strongly affected by radiative cooling, particularly for powerful ($\geq 10^{41}$ erg s$^{-1}$) and compact starbursts (see Silich et al. 2003; hereafter referred to as Paper I). Radiative cooling does not disturb the velocity of the outflow, nor the expected density drop ($\sim r^{-2}$) acquired as the flow moves away from the massive central cluster. Rapid cooling however, brings the temperature down in regions close to the starburst, favoring rapid recombination, and thus making the fast streaming outflow easy target of the UV radiation generated by the central stars. The prediction is then a much reduced size of the X-ray emitting zone and a fast moving HII region gas originating close to the central starburst.

M82 with its wind striking the "H$\alpha$ cap" at 10 kpc from the central source (see Devine & Bally 1999), is without a doubt the best example of a SGW in the Local Universe, injecting its newly processed metals into the intergalactic space (IGM). The central biconical wind in M82 however, presents an intricate structure that has little to do with the outcome from models of superwinds. In particular the X-ray and the H$\alpha$ filamentary structure as well as their spatial coincidence have presently no explanation. As stated by Strickland & Stevens (2000) the predicted X-ray luminosity, even using the adiabatic model of CC85, falls short by more than three orders of magnitude below the observed value. Strickland et al. (1997) also showed that the entropy of the X-ray emitting gas increases with distance from the plane of the galaxy, fact that is inconsistent with an adiabatic outflow model. On the other hand, the H$\alpha$ filamentary structure, beautifully evidenced by Subaru (see Ohyama et al. 2002 and references therein), is clearly not limb brightened and originates right at the base of the outflow reaching several kpc in a direction almost perpendicular to the galaxy plane. These facts are also very different from the superbubble features calculated by Suchkov et al. (1994) in which a complex filamentary structure develops at large distances (several kpc) from the galaxy disc, as a

[1] Instituto Nacional de Astrofísica Optica y Electrónica, AP 51, 72000 Puebla, México

[2] Instituto de Astrofisica de Canarias, E 38200 La Laguna, Tenerife, Spain

result of matter entraining the hot superbubble. There should be in fact very little resemblance between supergalactic winds freely expanding into the IGM and the calculations mentioned above in which a supershell contains always the possible outflow of the superbubble interior, and thus inhibits the development of a super galactic wind.

So far, all calculations in the literature have assumed that the energy deposition arises from a single central cluster that spans several tens of pc, the typical size of a starburst. However, recent optical, radio continuum, IR and UV observations (Ho 1997; Johnson et al. 2001; Colina et al. 2002; Larsen & Richtler 2000, Kobulnicky & Johnson 1999) have revealed a number of unusually compact young stellar clusters. These overwhelmingly luminous concentrations of stars present a typical half-light radius of about 3 pc, and a mass that ranges from several times $10^4$ $M_\odot$ to a few $10^6$ $M_\odot$. Clearly these units of star formation (superstar clusters, SSCs) are very different to what was usually assumed to be a typical starburst. Several of these entities have now been identified within a single starburst nucleus. For example, there are about 100 of them composing a flattened distribution of 150 pc radius at the center of M82, (see de Grijs et al. 2001, O'Connell et al. 1995), at least four within the nuclear zone of NGC 253 (Watson et al. 1996), and many of them in the Antenae (Whitmore et al. 1999).

Here we investigate the effects that the presence of several of these young compact clusters in a galaxy nucleus may have on the inner structure of well developed, or freely expanding, SGWs. Several aspects are considered in this two dimensional, first approach, to the 3-D interaction of multiple powerful winds. Among these, the metallicity of the superwind matter is here shown to have a profound impact on the inner structure of SGWs.

Here we study the interaction of several strong winds emanating from a collection of nearby superstar clusters, causing together the development of an extended region in which a plethora of crossing shocks collimate the general outflow while giving rise to an important soft X-ray contribution at large distances from the starburst nuclei. An extended region in which the layers of strong direct wind interactions lead, under strong radiative cooling, to a well developed network of elongated filaments. Section 2 displays our two dimensional calculations that use CC85 as initial condition in each of the superstar clusters. The evolution leads to multiple interactions, and the outcome of these, depending on the local values of density, temperature and metallicity, define when the flow is affected by strong radiative cooling. Section 3 discusses some of the observational consequences of such well collimated and structured outflows, in particular the resultant filling factor for different gas phases.

## 2. The interaction of winds from superstar clusters

There are two different evolutionary stages in the remnants produced by the large mechanical energy input rate associated to nuclear starbursts. The first one, the superbubble phase, is that during which a large-scale remnant evolves within the ISM, either within the disk or within the halo of the host galaxy. The second phase, the freely expanding supergalactic wind, in which an open channel in the ISM allows the supernova matter to freely stream into the intergalactic medium.

Weather one assumes a central source or multiple SSCs composing a starburst nucleus, the initial interaction with the host galaxy ISM will be rather similar. In particular, both sources of energy will lead to the development of a leading shock, able to sweep the surrounding ISM into a large-scale supershell, while a reverse shock will cause the full thermalization of the matter violently ejected by the central source or the multiple stellar clusters (see for example figure 1 in Heckman et al., 1990).

In both cases the thermalized hot gas within the superbubble will power the leading shock and thus promote the growth of a remnant able to eventually exceed the dimensions of the galaxy disk, causing via Rayleigh - Taylor instabilities the fragmentation and disruption of the supershell of swept up matter (see figure 4 in Tenorio-Tagle & Bodenheimer, 1988).

If one considers the presence of an extended halo (see Silich & tenorio-Tagle, 1998, 2001), the thermalized wind energy will generate an even larger supershell (see for example figure 6 in Strickland & Stevens, 2000), the velocity of which will continuously decay as more halo matter is incorporated. The presence of extended haloes (see e.g. Melo et al., 2002) is also supported by the ex-

istence of large-scale supershells in a large variety of galaxies (see for example Oey et al. 2002 and Marlowe et al., 1995).

Note that a supergalactic wind does not develop until the remnant exceeds the dimensions of the galaxy disk, or in case of an extended halo, until the superbubble reaches the outskirts of the galaxy (for a review see Heckman, 2001). At this moment, the leading and the reverse shocks cease to exist and the metals ejected by the star clusters will freely move into the intergalactic medium causing its contamination. It is also at this stage, once a channel has been carved in the ISM, once the superwind has developed, that major differences will arise from the assumption of a single or a multiple source of energy.

- In the case of a single compact source of energy, the free expanding wind has recently been found to be subjected to strong radiative cooling (see Paper I). Thus, the adiabatic model of Chevalier & Clegg (1985), used to calculate the extended X-ray emission of superwinds, leads to large overestimates. More realistic calculations, accounting for radiative cooling, have shown a much reduced volume, of only a few times the size of the starburst nucleus, able to generate X-rays. In this framework it is hard to understand the extended (more than 3 kpc long) X-ray emission of M82, a source that presents a more than 10 kpc long open channel into the intergalactic medium, and that clearly is in the supergalactic wind stage.

- Models with a single source predict also a strong $H_\alpha$ emission arising from the lateral walls of the disrupted supershell, continuously impacted by the UV radiation arising from the central source (see for example Suchkov et al. 1994, Tenorio-Tagle & Muñoz Tuñón 1997, 1998). The emission in such a case should be strongly limb brightened.

- Most models (perhaps with the only exception of Tenorio-Tagle & Muñoz Tuñón 1997, 1998, which accounts for the infall of matter into the central starburst) also end up with a remnant that presents a wide open waist along the galaxy plane (see figures in Tomisaka & Ikeuchi, 1988; Suchkov etal., 1994). This could measure several kpc in radius and is very different to the 150 pc radius estimated for the central perturbed area of M82.

The $H_\alpha$ emission of M82 is not limb brightened and arises from distinct filaments that emanate from the base of the outflow. This last point is also relevant as many models attempt to explain the filamentary structure with shell instabilities or with matter entraining the supershell at high distances from the galaxy plane (see Shuchkov et al. 1994).

In the following sections we derive the properties of supergalactic winds powered by multiple superstar clusters and stress the main differences in the resultant structure with respect to models that assume a single source.

### 2.1. The high metallicity outflow of supergalactic winds

Weather one considers one or multiple sources, the amount of metals expected from massive starbursts and thus to be found within SGWs, depends strongly on the assumed stellar evolution models. Two extreme possibilities were investigated by Silich et al. (2001) taking into consideration models with and without stellar winds by Maeder (1992), Woosley et al. (1993) and Thielemann et al. (1993) (see also Pilyugin & Edmunds 1996). The results indicate, first of all, that almost 40% of the mass gone into stars is violently returned to the surrounding medium by means of winds and supernovae. Of this, about 4% is in oxygen in the case of models without winds, and 1% for models that include winds. In either case, if one assumes that the metals mix efficiently with the stellar hydrogen envelopes of the progenitors, within the radius that encompasses the stellar cluster, then the metallicity of the superwind can be calculated. As shown by Silich et al. (2001) for the case of superbubbles, this reaches supersolar values in all considered cases, showing a maximum within the first 7 - 8 Myr of the evolution. Such values have recently been confirmed through X-ray observations by Martin et al. (2002) for NGC 1569.

The large metallicities expected from massive star clusters are to have a strong impact on the cooling properties of the outflow and thus also

on the observational properties of freely expanding superwinds. Figure 1 shows the run of the expected metallicity of the matter ejected by a massive burst of stellar formation, using oxygen as tracer and stellar evolution models with winds, as a function of time. The estimate is for a coeval starburst powered during 40 Myr of evolution (until the last 8 $M_\odot$ star explodes as supernova in a coeval starburst model). The outflow, before the supernova era, will display a metallicity similar to that of the gas cloud out of which the starburst formed. Thus the gas ejected first presents the metallicity here assumed for the host galaxy ($Z_{ISM}$ = 0.1 $Z_\odot$). The supernova products however, rapidly enhance the metallicity of the outflow, reaching values well above $Z_\odot$ for at least 20 Myr of the evolution. Afterwards, once the yield is reached, the outflow steadily approaches the metallicity values of the host galaxy. Starburst models, with single or multiple energy sources, are to account for the high metallicities emanating from the massive centers of star formation, to derive in a consistent manner the impact of radiative cooling in the resultant outflows.

### 2.2. Boundary and initial conditions

Several two dimensional calculations using as initial condition CC85 adiabatic flows have been performed with the explicit Eulerian finite difference code described by Tenorio-Tagle & Muñóz-Tuñón (1997, 1998). This has been adapted to allow for the continuous injection of multiple winds (see below).

Here we consider the winds from several identical SSCs, each with a mechanical energy deposition rate equal to $10^{41}$ erg s$^{-1}$. The energy is dumped at every time step within the central 5 pc of each of the sources following the adiabatic solution of Chevalier & Clegg (1985). The separation between the sources is clearly arbitrary. We have considered two different configurations. The first one with three SSCs placed at 60 pc and 90 pc from the central one, all of them sitting on a plane. A second configuration considers only two sources sitting at 30 pc and 60 pc away from the symmetry axis. Several calculations were made to reasure that the spatial resolution used, led to a convergent solution. All calculations here presented were made with the same numerical resolution of half a pc and all of them with an open boundary along the grid outer edge. The time dependent calculations do not consider thermal conductivity but do account for radiative cooling, with a cooling law (Raymond et al. 1976) scaled to the metallicity assumed for every case. Here we present the results of different cases for which the assumed metallicity of the winds was set equal to 3$Z_\odot$ and 10$Z_\odot$, justified by the high metallicity outflows expected from massive bursts of star formation (see Figure 1).

In all cases it is assumed that at the heart of each SSC, within the region that encompasses each of the recently formed stellar clusters ($R_{SB}$), the matter ejected by strong stellar winds and supernova explosions is fully thermalized (CC85, see also Canto et al. 2000 and Raga et al. 2001). This generates the large overpressure responsible for the mechanical luminosity associated to each of the super clusters. Within each star cluster region, the mean total mechanical energy $L_{SB}$ and mass $\dot{M}_{SB}$ deposition rates, control, together with the actual size of the star forming region $R_{SB}$, the properties of the resultant outflow. The total mass and energy deposition rates define the central temperature $T_{SB}$ and thus the sound speed $c_{SB}$ at the cluster boundary. As shown by CC85 at the boundary $r = R_{SB}$, the flow starts expanding with its own sound speed. There is however a rapid evolution and as matter streams away it is immediately accelerated by the steep pressure gradients and rapidly reaches its terminal velocity ($V_\infty \sim 2c_{SB}$). This is due to a fast conversion of thermal energy into kinetic energy of the resultant winds. In this way, as the winds expand, their density, temperature and thermal pressure will drop as $r^{-2}$, $r^{-4/3}$ and $r^{-10/3}$, respectively (see CC85). The flow is then exposed to suffer multiple interactions with neighboring winds and as shown in Paper I, it is also exposed to radiative cooling. For the former, the issue is the separation between neighboring sources and for the latter the local values of density, temperature and metallicity. Radiative cooling would preferably impact the more powerful and more compact sources, leading to cold ($T \sim 10^4$ K) highly supersonic streams (see Paper I).

### 2.3. The structure of supergalactic winds

Figure 2 compares the initial stages of cases 1 and 2, that consider three equally powerful ($L_{SB}$

$= 10^{41}$ erg $s^{-1}$) superstar clusters sitting at 0, 60 and 90 pc from the symmetry axis. All of them with an $R_{SB} = 5$ pc, produce almost immediately a stream with a terminal velocity equal to 1000 km $s^{-1}$. The only difference between the two cases is the assumed metallicity set equal to $3Z_{\odot}$ in case 1 (upper panels) and $10Z_{\odot}$ in case 2 (lower panels). At t = 0 yr the three clusters are embedded in a uniform low density ($\rho = 10^{-26}$ g $cm^{-3}$) medium. Thus our calculations do not address the development of a superbubble, nor the phenomenon of breakout from a galaxy disk or the halo, into the IGM. The initial condition assumes that prior events have evacuated the region surrounding the superstar clusters, and we center our attention on the interaction of the supersonic outflows.

Figure 2 shows the resultant initial stages of cases 1 and 2. The various panels display the run of density and velocity (left panels) and that of temperature (next four panels) in four temperature ranges: The regime of H recombination $10^4$ K - $10^5$ K, followed by two regimes of soft X-ray emission $10^5$ K - $10^6$ K, and $10^6$ K - $10^7$ K and the hard X-ray emitting gas with temperatures between $10^7$ K - $10^8$ K.

The crowding of the isocontours in the figures indicate steep gradient both in density or in temperature and velocity, and thus indicate the presence of shocks and of rapid cooling zones. In the temperature plots one can determine the distance ($\sim$ 30 pc in case 1 and 15 pc in case 2) within the diverging outflows emanating from each of the superstar clusters, at which strong radiative cooling (in agreement with our analytical estimates in Paper I) becomes important in the two cases.

The interaction of neighboring supersonic winds causes the immediate formation of their respective reverse shocks, and of a high pressure region right behind them. The pressure (and temperature) reaches its largest values at the base of the interaction plane, exactly where the reverse shocks are perpendicular to the incoming streams. The high pressure gas then streams into lower pressure regions, defining together with radiative cooling, how broad or narrow the high pressure zones, behind the reverse shocks, are going to be. Radiative cooling occurs in every parcel of gas at the rate prescribed by its local density, temperature and metallicity. If cooling is avoided at least partially or temporarily, as in the first case, the high pressure region between the reverse shocks would drive them against the incoming streams, and very shortly they would acquire a oblique standing stable configuration to be retained for as long as the winds continue to interact (see Figure 2, upper panels).

This also happens if cooling is fast enough, the oblique reverse shocks rapidly acquire a standing location, however in these cases, the loss of temperature behind the shocks is compensated by gas condensation, leading, as in the second case (see Figure 2, bottom panels), to narrow, dense and cold filaments. The drastic drop in temperature occurs near the base of the outflow, where the gas density is large and radiative cooling is exacerbated. The dense structures are then launched at considerable speeds ($\sim$ several hundreds of km $s^{-1}$) from zones near the plane of the galaxy (see Figure 2 lower panels). These dense and cold structures are easy target to the UV radiation produced by the superstar clusters and thus upon cooling and recombination are likely to become photoionized. Note however that as the free winds continue to strike upon these structures, even at large distances from their origin, the resultant cold filaments give the appearance of being enveloped by soft X-ray emitting streams.

All of these shocks are largely oblique to the incoming streams and thus lead to two major effects: a) partial thermalization and b) collimation of the outflow. These effects result from the fact that only the component of the original isotropic outflow velocity perpendicular to the shocks is thermalized, while the parallel component is fully transmitted and thus causes the deflection of the outflow towards the shocks. This leads both, to an efficient collimation of the outflow in a general direction perpendicular to the plane of the galaxy, and to a substantial soft X-ray emission associated with the dense filamentary structure, extending up to large distances (kpc) from the plane of the galaxy. In the figures one can clearly appreciate that the oblique shocks, confronting the originally diverging flows, lead to distinct regions where the gas acquires very different temperatures, and thus that will radiate in different energy bands.

Figures 3 and 4 show the time sequence of cases 1 (with Z = 3 $Z_{\odot}$) and 2 (with Z = 10 $Z_{\odot}$), respectively, until they reach dimensions of one kpc, together with the final temperature structure split-

ted into the four temperature regimes considered earlier (last four panels).

The stream of gas behind the reverse shocks leads eventually to the establishment of crossing shocks at the tips of the oblique structures (see Figure 3), which are to become also stationary as the flow is effectively channeled into the IGM.

As in the case of colliding stellar winds from binary systems (see Stevens, Blondin & Pollock 1992) a variety of dynamical instabilities are found to dominate the shocked region, particularly when strong radiative cooling sets in (see Figure 4). These lead to the various loops and twists along the dense filamentary structures, which nevertheless do not impede that the outflow reaches large distances away from the galaxy plane. The loops and twists along these structures promote also a larger cross-section to the incoming free wind and partly thermalized wind and thus lead to regions of enhanced soft X-ray emission clearly associated to the twisted H$\alpha$ filaments (see Figure 4).

Figure 5 displays the results from a final case in which two superstar clusters sitting at 30 and 60 pc away from the symmetry axis interact to shape the inner structure of a superwind. The calculation also assumes a Z = 10 $Z_{\odot}$. As in case 2, elongated filaments result from the interaction of the high metallicity winds, channeling into the IGM most of the energy deposited by the SSCs. Note that, as in the preceding cases, about 50% or less of the energy deposited by the most outer SSC is lost in the radial direction, while the rest, as well as that deposited by other energy sources, is fully driven into the IGM.

### 2.4. Self-collimated supergalactic winds

The high degree of collimation attained in our calculations, that composes a SGW from a collection of energetic neighboring superstar clusters, results from the simple fact of having placed the individual wind sources of equal strength, all of them, in a preferential plane. In this way, it becomes irrelevant if they all sit on a flattened disk, or a ring. As long as they all sit near a preferential plane, the interaction of neighboring supersonic diverging flows will promote the multiple standing reverse oblique shocks and crossing shocks that will unavoidably lead to a remarkably efficient self-collimation. Collimation that does not required of a torus or a thick disk of ISM. If all superstar clusters sit on a plane, only a fraction of the energy provided by the ones sitting at the most outer extremes of the cluster distribution will interact with the general ISM. However, most of the energy produced by the collection of sources will be rechanneled by the standing oblique shocks resulting from neighboring interactions, to compose a broad base supersonic jet, capable of self-collimation. The base of the outflow will then have dimensions similar to the flattened cluster distribution and as shown above, depending on the individual energetics, proximity and metallicity, the general outflow is to generate a dense and cold filamentary structure as well as a kpc extended soft X-ray emitting region. A rich structure that could not arise if one assumes a free expanding wind that emanates from a single SSC.

A wider jet structure may be generated in cases in which the population of SSCs do not have the same mass and thus equal mechanical energy input rates. Under such conditions the oblique shocks will present standing configurations more inclined over the less energetic clusters and this will lead to the fanning and broadening of the outflow, and to the inclination of the filamentary pattern.

## 3. Discussion

From the starburst synthesis models (see Leitherer & Heckman 1995) one knows that a superstar cluster with a total mass in stars (say $M_*$ $\sim 10^6$ $M_{\odot}$) produces an almost constant ionizing photon flux ($F_{uv} \sim 10^{53}$ photons $s^{-1}$) during the first few (3-4) Myr and then abruptly, it begins to decrease as $t^{-5}$ as the most massive stars begin to evolve away from the main sequence to eventually end up as supernovae. This implies that after 10 Myr of evolution, the ionizing flux would be more than two orders of magnitude smaller than its original value and thus the UV radiation will be unable to ionized the original HII region volume, limiting to 10 Myr the duration of the HII region phase. On the other hand, the mechanical energy deposition from such a cluster leads to an almost constant value ($\sim 10^{40}$ erg $s^{-1}$) over a much longer time span, as it includes the correlated supernovae from stars down to 8 $M_{\odot}$ with an evolutionary time of 40 - 50 Myr. And thus the supernova phase is 4 or 5 times longer than

the HII region phase.

Under such circumstances, if one considers a starburst nucleus composed by several SSCs generated at different times, then the time span during which the isotropic winds from these may interact, the coherence phase, is limited to 40 Myr. Within this time, newly born clusters will have the capability of causing the ionization of the structure produce by interacting winds that emanate even from cluster with an age in excess of 10 Myr. During the coherence phase, some of the SSCs will also be producing highly metallic outflows (see Figure 1), the interaction of which will lead to a filamentary wind structure.

A comparison of the last calculated time of cases 1 and 2, each with 3 SSCs dumping $10^{41}$ erg $s^{-1}$ (see Figures 3 and 4), when the redirected outflow has reached dimensions of almost 1 kpc, allows for an estimate of the filling factor occupied by gas at different temperatures. The hot (T $\geq 10^5$ K) gas occupies almost 70% in case 1 and 30% in case 2, of the total area. The warm gas (T $\leq 10^5$ K) fills most of the remaining volume although the dense and cold enhancements evident in Figure 4 occupy about 40% of the superwind cross-sectional view. There is also a small volume around the SSCs that present temperatures that will allow the gas to radiate in the hard X-ray regime (see last two plots in Figures 3 and 4). This numbers are to be compared with the results from the outflow produced by an equally energetic ($3 \times 10^{41}$ erg $s^{-1}$) single cluster. Following Paper I, we have calculated the temperature distribution and thus the radius at which radiative cooling (assuming Z = $3Z_{\odot}$) sets in for a clusters with a radius of 95 pc (the size of the cluster distribution used in cases 1 and 2). The temperature of such a free streaming outflow plummets to $10^4$ K at 480 pc (instead of $\sim$ 10 kpc obtained if one assumes an adiabatic flow). In such a case, if one considers a similar volume to that displayed in Figures 3 and 4, then the hot gas (T $\geq 10^5$ K) filling factor will be 37.5% and the rest of the volume will be filled with gas capable of being re-ionized by the stellar photon flux. When comparing the results from single and multiple sources, it is central to notice the spatial distribution of the various resultant gaseous phases. Cases with multiple SSCs lead to the spatial co-existence of the X-ray (T $\geq 10^5$) and the dense and cold (T $\leq 10^5$ K) emitting filaments (see panels 5 and 6 in Figures 3 and 4). In the case of a single source of energy the X-ray emitting gas is not in direct contact with the cooler medium along the outflow. i. e. the structure of the outflow is concentric, with the X-rays emanating only from the most central regions.

The collimation caused by the various oblique and crossing shocks in the multiple source cases, that makes the superwind avoid the diverging outflow inherent to isotropic single source cases, channels almost five times more energy within the computational area above considered. In case 1 the thermal and kinetic energy of the hot phase dominate with 26% and 57%, respectively, over the 17% kinetic energy found in the gas with T $\leq 10^5$ K. These numbers are to be compared with the results from the single source case described above that present within a similar computational volume, a 68% and 27% as thermal and kinetic energy of the hot gas, while only a 5% of the total appears as kinetic energy of the gas with T $\leq 10^5$ K.

The origin of the X-rays in nuclear starburst regions and of the filamentary structure, as seen in H$\alpha$ in M82, have been ascribed to features seen in models that consider various stages in the development of hot superbubbles powered by a central starburst. Models that present a single reverse shock, an outer super shell and thus models that have little to do with a free expanding SGW. Note that if the wind of M82 has reached the H$\alpha$ cap at 10 kpc from the galaxy disk, and is expanding with say, 1000 km $s^{-1}$, then the free streaming outflow started at least 10 Myr ago. During that time the base of the outflow has managed to preserve a comparatively small dimension (radius $\sim$ 150 pc) implying a very efficient channeling of the deposited energy in a direction away from the disk of the galaxy. There is also a growing evidence of large-scale features in starburst galaxies, caused by an important stellar energy input rate and the richness of structure within the ISM. However, in most of the cases the evidence for a freely expanding supergalactic wind is only marginal. In the case of NGC 253, its extended X-ray emitting bubble is much smaller than the dimensions of the dusty galaxy halo found by Melo et al. 2002, implying therefore that it is still evolving along the superbubble phase. Similar conclusions were drawn by Martin et al. (2002) for NGC 1569:

"The X-ray color variations in the halo are inconsistent with a free-streaming wind and probably reveal the location of shocks created by the interaction of the wind with a gaseous halo". Several more dwarf starburst galaxies were considered by Legrand et al. (2001) where the energetics inferred from the central clusters were compared with the limit for mass ejection derived by Silich & Tenorio-Tagle (2001). In all considered cases the bulk of the galaxy sample lie below the limit required to reach the galaxies outskirts.

From the results of section 2, it is clear that the inner structure of super galactic winds strongly depends on the energy and mass deposition history. In particular we have shown that the richness of structure is largely enhanced when the presence of superstar clusters, their powerful winds, and possible interaction within a single starburst nucleus, are taken into consideration. These considerations open a new set of possibilities. Issues such as the intensity of star formation in every superstar cluster, which defines their mechanical luminosity, their age which also impacts on the metallicity of the ejected matter, as well as the number of superstar clusters, their compactness, and their position within a starburst nucleus, are all relevant new parameters that allow for the co-existence of X-rays and optical emitting features, even at large distances from the source of energy.

From our results it is clear that a plethora of structure, both in X-rays and in the optical line regime, may originate from the hydrodynamical interaction of multiple winds. The interaction leads to multiple standing oblique (reverse) shocks and crossing shocks able to collimate the outflow away from the plane of the galaxy. In our two dimensional simulations, these are surfaces that become oblique to the incoming streams and thus evolve into oblique shocks that thermalize only partly the kinetic energy of the winds causing a substantial X-ray emission at large distances away from the galaxy plane. Surfaces that at the same time act as collimators, redirecting the winds in a direction perpendicular to the plane occupied by the collection of SSCs. Radiative cooling behind the oblique shocks leads, as soon as it sets in, to condensation of the shocked gas, and thus to the natural development of a network of filaments that forms near the base of the outflow, and stream away from the plane of the galaxy to reach kpc scales. Under many circumstances these filaments develop right at the base of the outflow and for all cases the prediction is that they are highly metallic. Note that the speed with which the calculated filaments raise above the galaxy plane is $\sim$ 600 km s$^{-1}$, a value in excellent agreement with the measured deprojected velocities of the filaments in M82 (Shopbell & Bland-Hawthorn, 1998). Hydrodynamic instabilities play also a major role on the filamentary structure. Non-linear thin shell instabilities as studied by Vishniac (1994) as well as Kelvin Helmholtz instabilities broaden, twist and generally shape the filaments as these stream upwards and reach kpc scales. The broadening of the filaments causes their interaction with the free winds, thermalizing further the rapid stream while leading to the development of soft X-ray emitting zones that envelope the densest structures.

The surfaces that develop at the plane of interaction between two wind sources are in our two dimensional approach depicted as vertical structures. From these, the only real vertical structure is the filament that forms along the symmetry axis in our last case. This results from the convergence of multiple winds arising from superstar clusters sitting on a ring 30 pc away from the symmetry axis. It is indeed necessary to perform our calculations in three dimensions to see the final outcome. Note however that the lateral side of all interaction planes will be launched into the highest pressure regions i.e. close to the base of the interaction, and thus it is very likely that they would be destroyed by the collision with other similar structures arising from other interaction planes. The final outcome is thus expected to be very similar to that depicted by our two dimensional simulations. Nevertheless three dimensional simulations are now underway and will also consider a variety of stellar masses and ages of the superstar clusters, as well as different locations and numbers within a starburst region.

Figure captions.

Fig. 1.— The metallicity of the ejected matter. The metallicity of freely streaming outflows produced by massive burst of star formation (in solar units) is plotted against the evolutionary time. The outflow emanates from a coeval starburst able to thermalize and mix all the newly processed metals with the stellar hydrogen envelopes of the progenitors. The curve is derived for stellar evolution models with winds (see Silich et al. 2001) using oxygen as tracer. The metallicity of the outflow reaches super solar values during most of the evolution and is strongly reduced down to the original assumed ISM values, once the production of oxygen reaches its yield.

Fig. 2.— Two dimensional superwinds. The various panels in every row represent cross-sectional cuts along the computational grid showing: isodensity contours with a separation $\Delta$ log $\rho = 0.1$ and the velocity field for which the longest arrow represents $10^3$ km s$^{-1}$. The following four panels display isotemperature contours, within the range $10^4$ K - $10^5$ K, $10^5$ K - $10^6$ K, $10^6$ K - $10^7$ K and $10^7$ K - $10^8$ K, respectively. Each of the superwinds has a power of $10^{41}$ erg s$^{-1}$ and a radius of 5 pc. The evolution of each wind starts from the adiabatic solution of CC85. The distance between consecutive tick mark = 25 pc in all figures. Thus, the size of the plots is 100 pc $\times$ 250 pc. The evolution time for the two models is: $1.62 \times 10^5$ yr and $1.79 \times 10^5$ yr. The assumed metallicities were Z = 3 $Z_\odot$ (upper panels), and 10 $Z_\odot$ (lower panels).

Fig. 3.— The same as Figure 2 for Z = $3Z_\odot$. The evolutionary time in the four first panels is 1.62 $\times$ $10^5$ yr, 4.17 $\times$ $10^5$ yr, 9.4 $\times$ $10^5$ yr and 1.25 $\times$ $10^6$ yr. The last four panels show the temperature distribution, as in Figure 2, for the last calculated model. The size of the plots displays the whole computational grid: 100 pc $\times$ 1 kpc.

Fig. 4.— The same as Figure 3 for Z = $10Z_\odot$. The evolutionary times of the first four panels is 1.79 $\times$ $10^5$ yr, 4.82 $\times$ $10^5$ yr, 1.05 $\times$ $10^6$ yr and 1.39 $\times$ $10^6$ yr, respectively.

Fig. 5.— The same as Figure 3 for Z = $10Z_\odot$. The calculation considers only two superstar clusters far from the symmetry axis. The evolutionary times of the first four panels is 1.8 $\times$ $10^5$ yr, 4.94 $\times$ $10^5$ yr, 1.05 $\times$ $10^6$ yr and 1.4 $\times$ $10^6$ yr, respectively.

We thank an anonymous referee for multiple suggestions and comments. The authors acknowledge support from CONACYT - México, research grant 36132-E and from the Spanish Consejo Superior de Investigaciones Científicas, grant AYA2001 - 3939.

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